Exclusive electroproduction of vector mesons

$\mathcal{L}$. *Favart*

I.I.H.E.
Université Libre de Bruxelles

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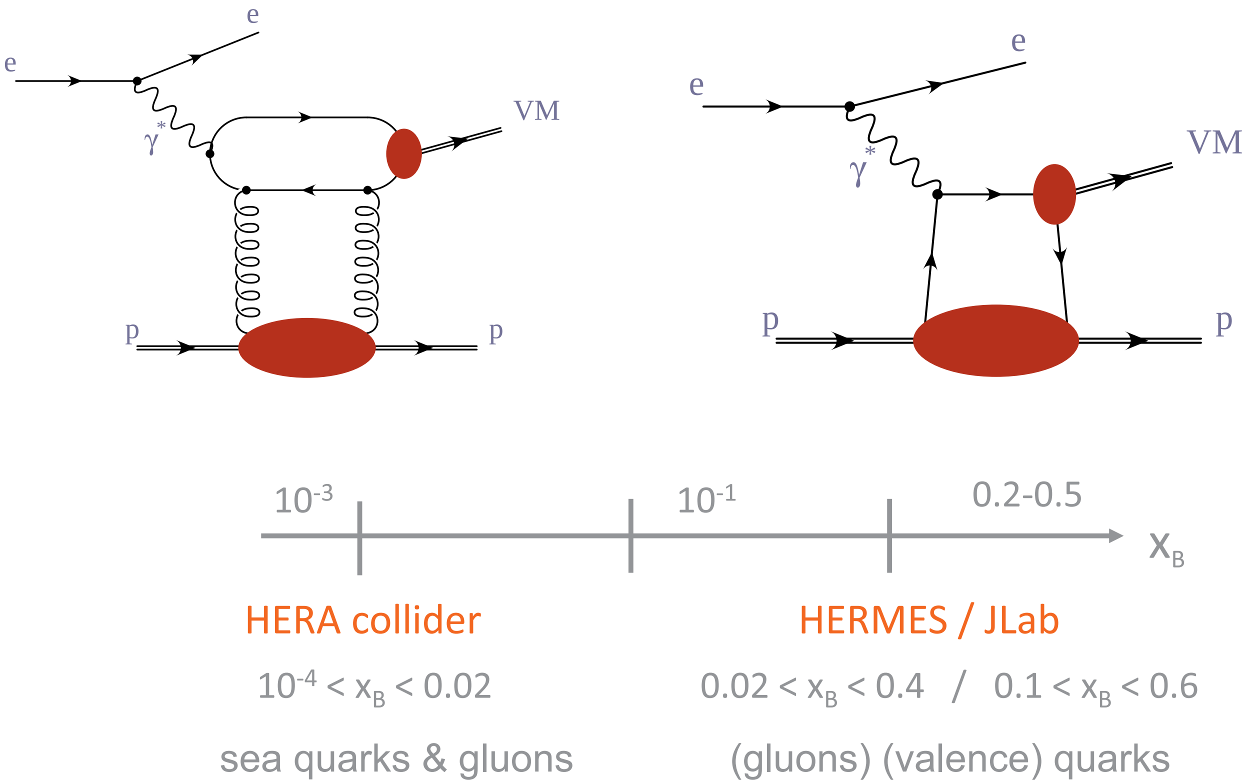
Exclusive Vector Meson production



In this talk: Cross section and SDME measurements

Interpret and confront them (low $\leftrightarrow$ high W)

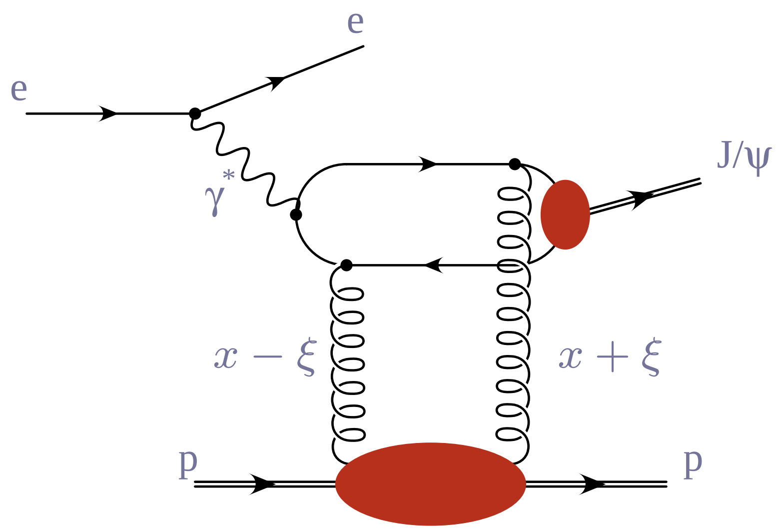
only unpolarised lepton beam and unpolirised target (p beam)

presence of a hard scale: $Q^2 >> 1$ GeV^2 or heavy meson

only elastic, i.e. no p-diss final state

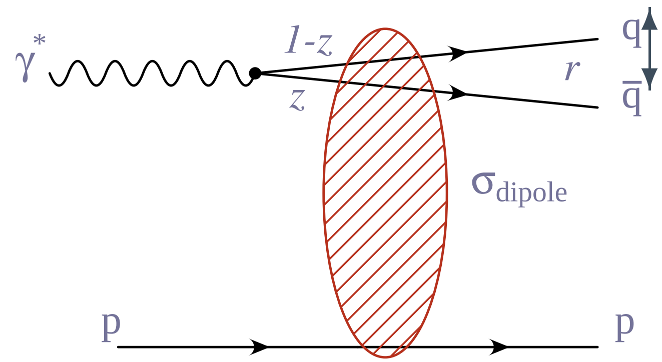
Two theoretical approaches

QCD in Breit frame



- "exact" QCD calculation possible
- $\int GPD(x,\xi,Q^2)\ dx$
- J/Ψ wave function
- GPDs$(x,\xi,t;\mu)$ build from the PDFs with a skewing effect and a t dependence

Colour Dipole



In the proton rest frame:

- γ^* fluctuates in $q\bar{q} + q\bar{q}g + ...$

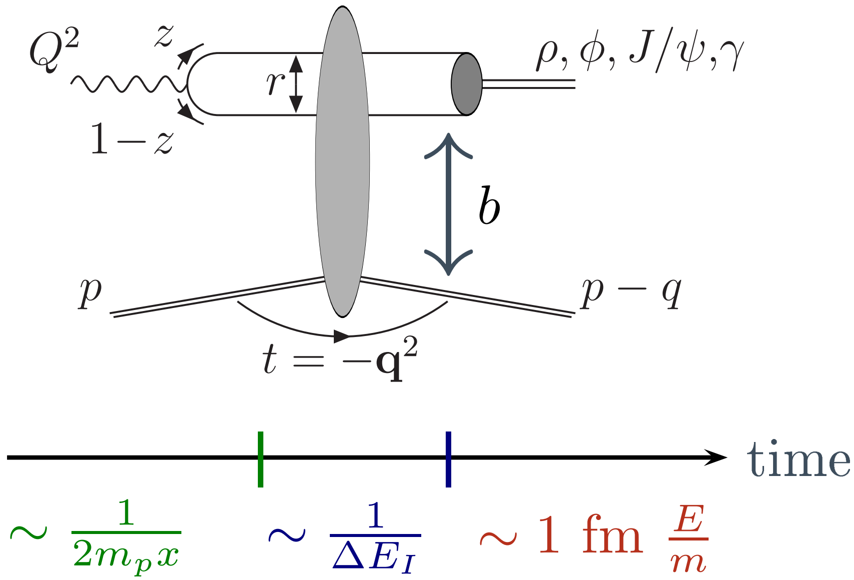
$$\sigma = \int dr^2 \psi^{in}(r,z,Q^2)\ \sigma_{\mathrm{d}}^2\ \psi^{out}(r,z,Q^2)$$

- ψ^{in} calculable
- σ_{d} is modelised (e.g. two gluons)
- integrated over trans. $q\bar{q}$ separation r

VM production in Colour Dipole approach

- at large energy, for $\mathcal{A}_L$ (large Q^2 or heavy quarks):

1. γ fluctuates in $q\bar{q}$ dipole: QED γ wave function Ψ_γ
2. dipole-proton interaction: universal $\sigma_{dip}(r, z, b)$
3. $q\bar{q}$ recombination into VM



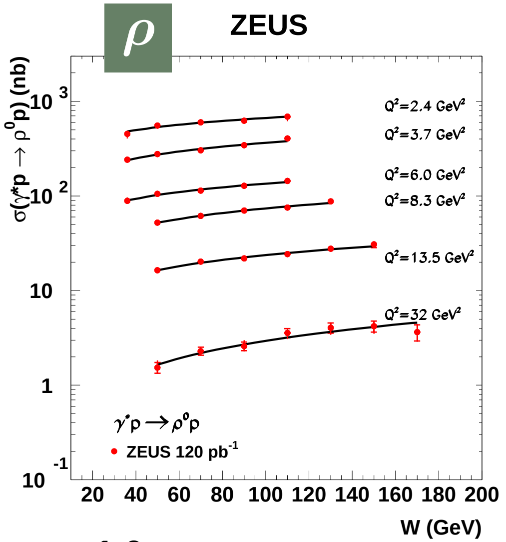
- The scaning radius r is expected to decreases with increasing Q^2 or M_V

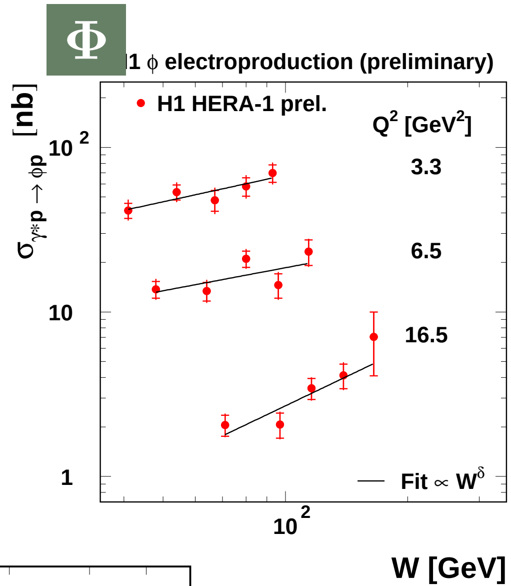
$\Rightarrow$ universal scale: $\mu^2 = z(1-z)(Q^2 + M_V^2)$

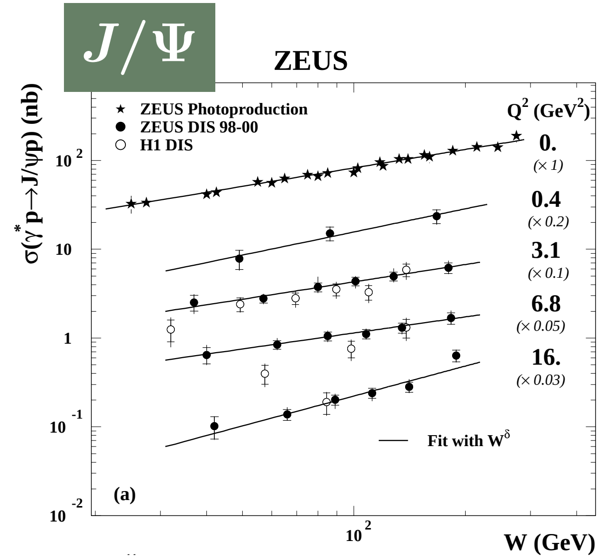
- for $\mathcal{A}_L$ (large Q^2) or heavy quarks: $z \simeq 1/2 \Rightarrow \mu^2 \simeq (Q^2 + M_V^2)/4$

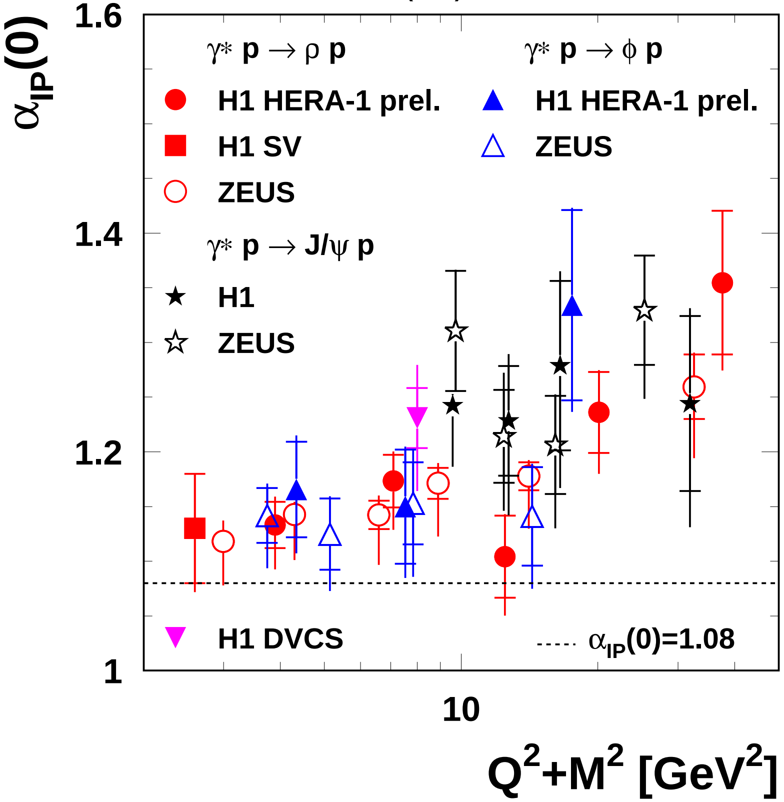
- for light quarks, $\mathcal{A}_T$: contrib. from end points $z = 0, 1 \Rightarrow \mu^2$ can be small even for large $Q^2 \Rightarrow$ soft contributions. Some models introduce k_L for quarks to avoid the singularities.

High W: W dependences









$$\alpha_{I\!P}(0) = 1 + \delta/4 + \alpha'_{I\!P}/\langle|t|\rangle$$

$$\alpha'_{I\!P} = 0 - 0.25\ \mathrm{GeV}^{-2}$$

- Common hardening of $\alpha_{I\!P}(0)$ with $Q^2 + M^2$ for all VM and DVCS

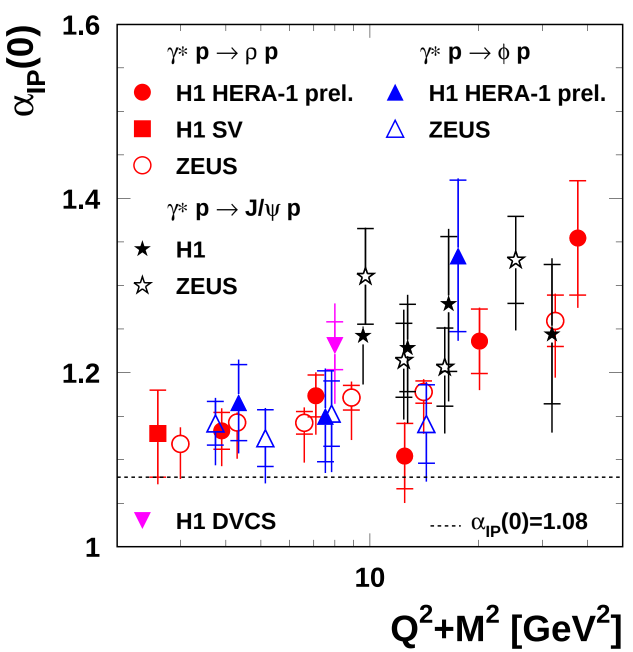
$\Rightarrow$ Transition from soft to hard regime with $Q^2 + M^2$
but soft contrib. up to 20 GeV^2 (σ_T?)

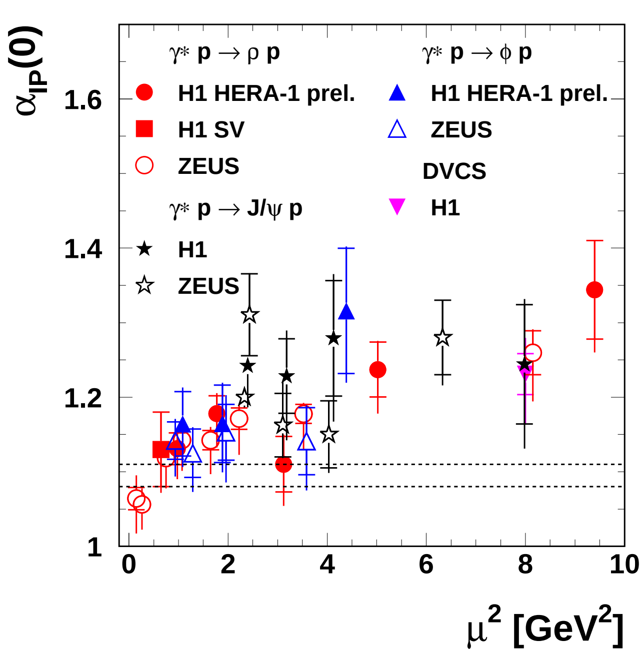
High W: W expected dependence

- $\sigma \sim W^{\delta} \sim |x\, g(x,\mu^2)| \Rightarrow$ hard W dependence: signature of a hard scale

$\Rightarrow \delta = 4(\alpha(0) + \alpha' t - 1)$ larger than soft (+ skewing effects)

$\Rightarrow$ **Hard scale: $\delta, \alpha(0)$: universal with $\frac{Q^2+M_X^2}{4}$**





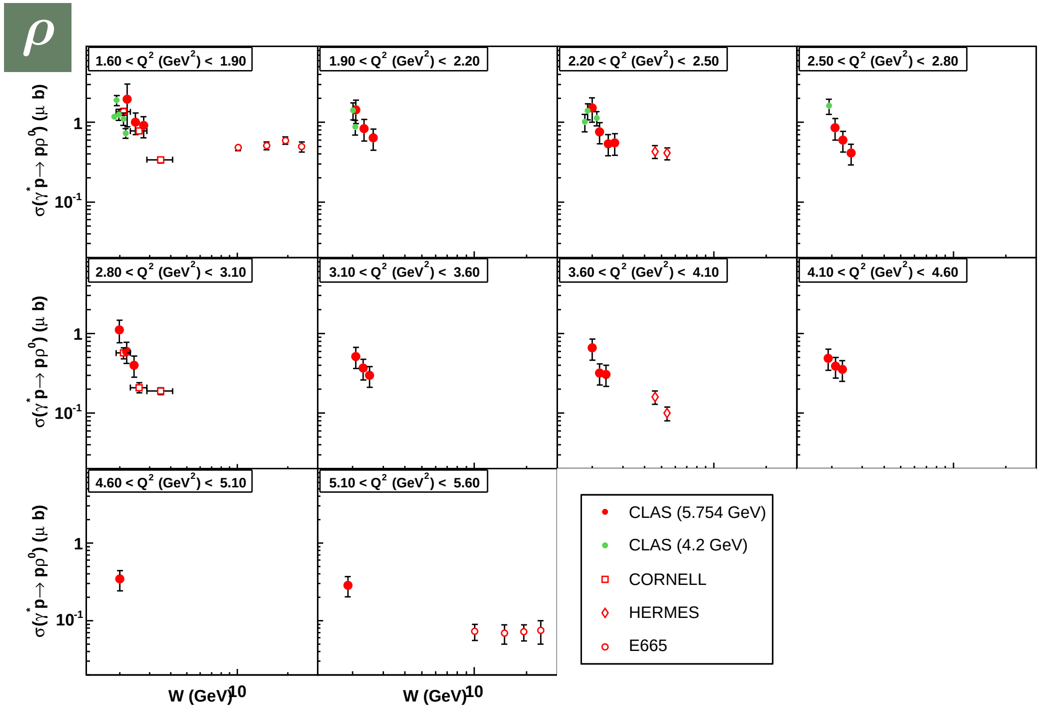
DVCS is like DIS, the photon (at LO) interacts directly with a resolved quark.

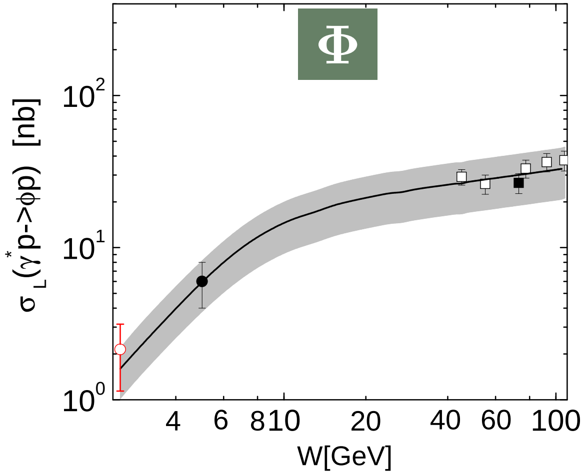
for all: $\mu^2 = Q^2 + M_X^2$

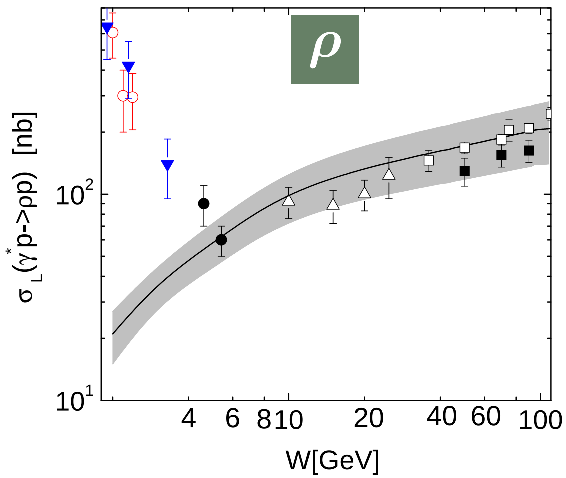
for VM: $\mu^2 = \frac{Q^2+M_X^2}{4}$

for DVCS : $\mu^2 = Q^2$

Low W: W dependences

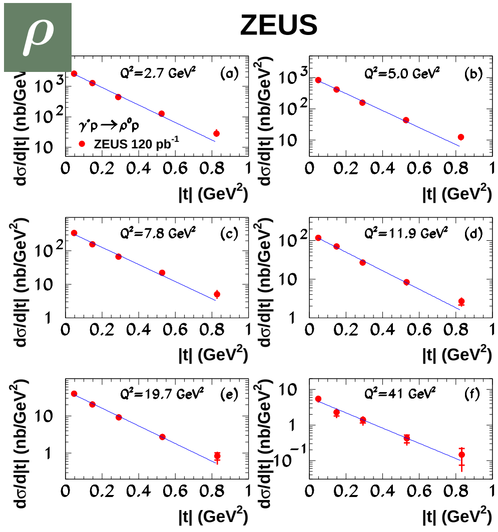


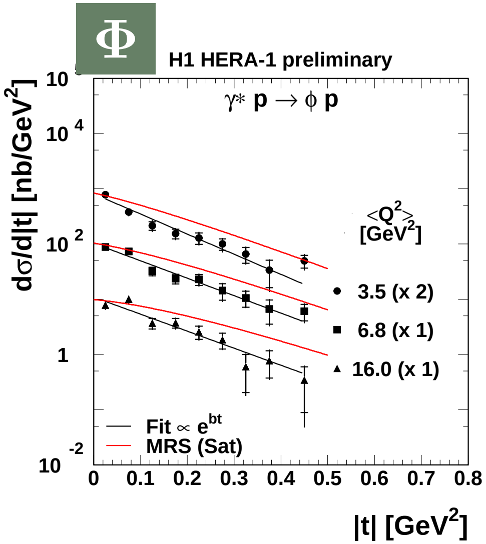


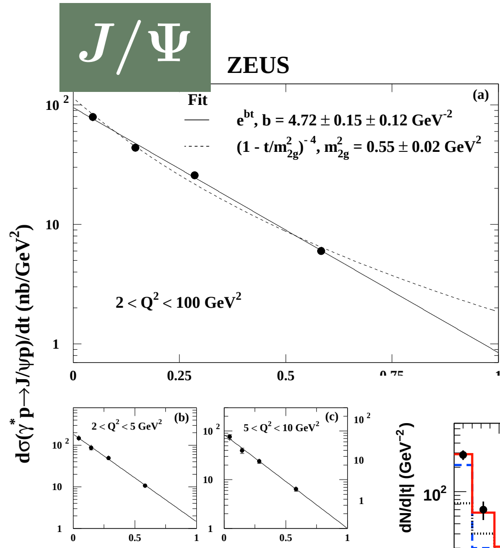


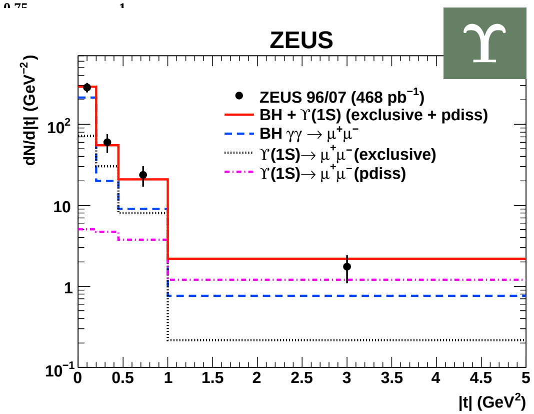
- GPD based predictions of S.Goloskokov and P.Kroll (GK) describe well the **Φ** exclusive production down to the lowest $\boldsymbol{W}$
- But cannot describe the $\boldsymbol{\rho}$ production for $\boldsymbol{W} < \mathbf{5}$ GeV
- Described in GPD based model: M.Vanderhaeghen, P.Guichon and M.Guidal (VGG) with an ad hoc D term.

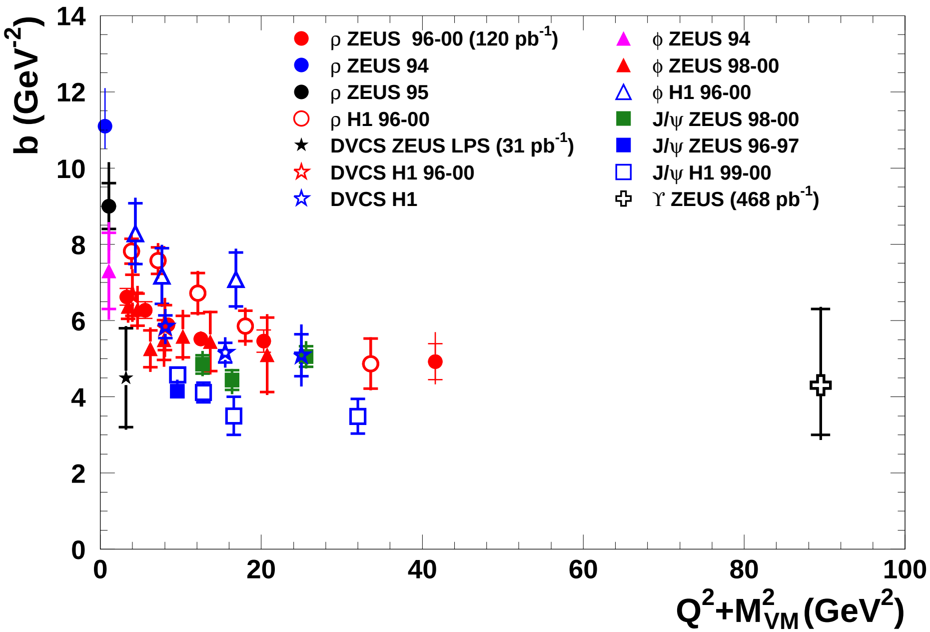
t dependences











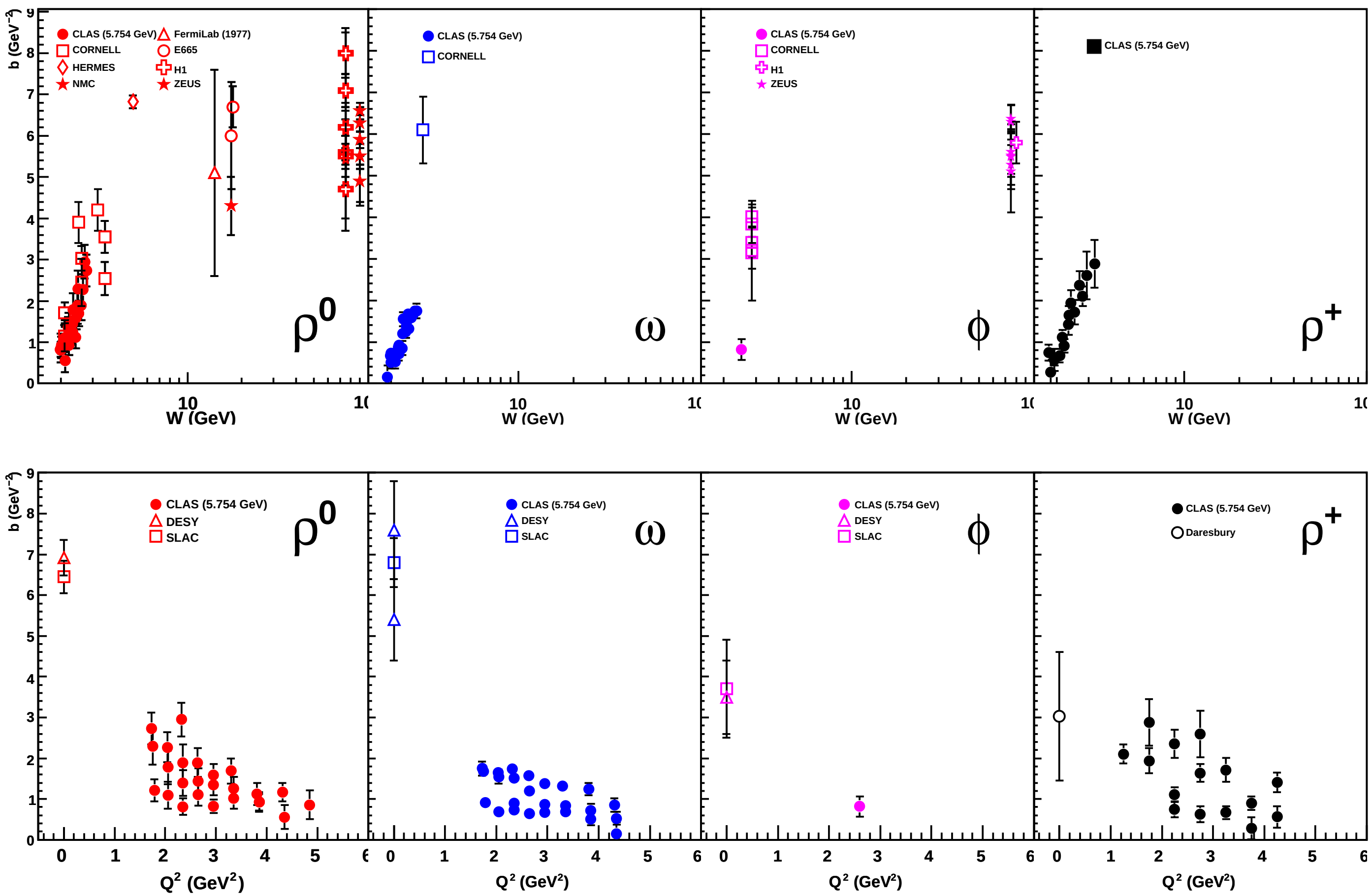
fit of $e^{-b|t|}$

$$b = b_{dip} \oplus b_{exch} \oplus b_p$$

- t slope hardening with $Q^2 + M^2$ for all VM and DVCS

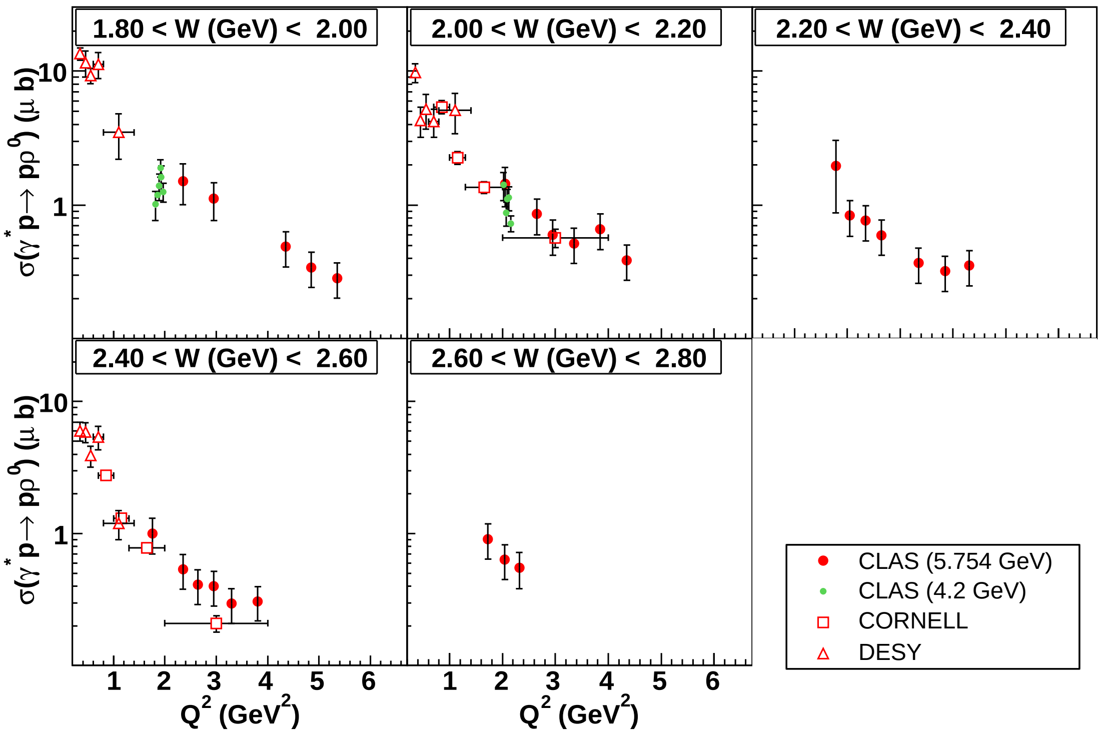
$\Rightarrow$ Transition from soft to hard regime with $Q^2 + M^2$
effect of VM WF ?

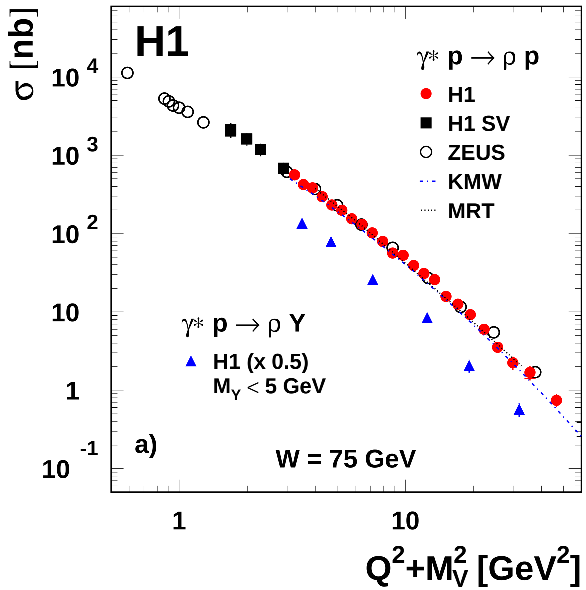
Low W: b slopes for different VM

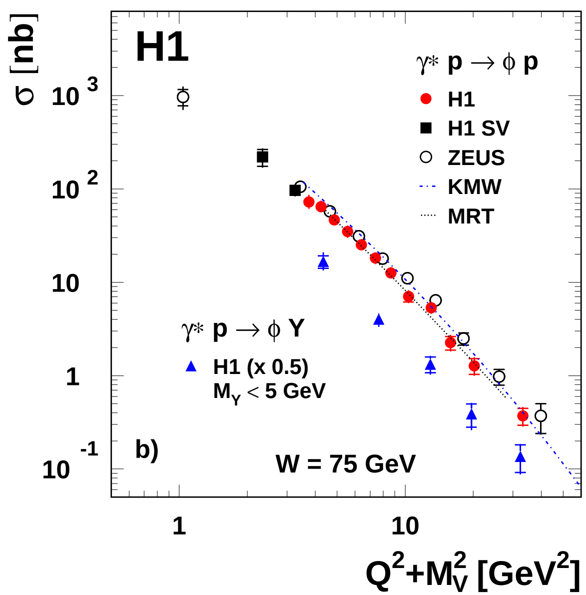


- first increase at low W then flat
- decreases with Q^2 as at high W (photon size effect ?)
- how do we interpret such low b values ? (smaller than the p)

Q^2 dependence



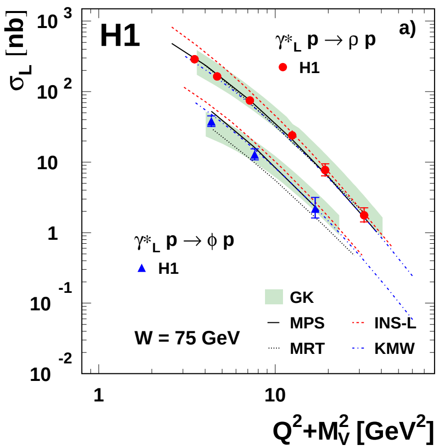


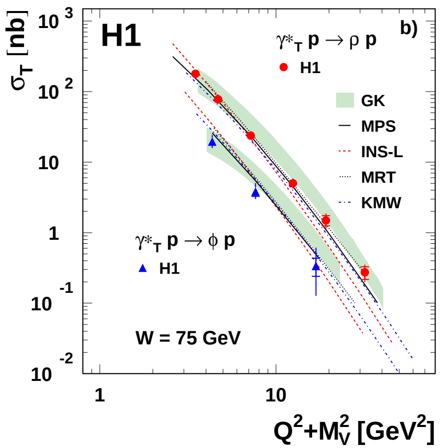


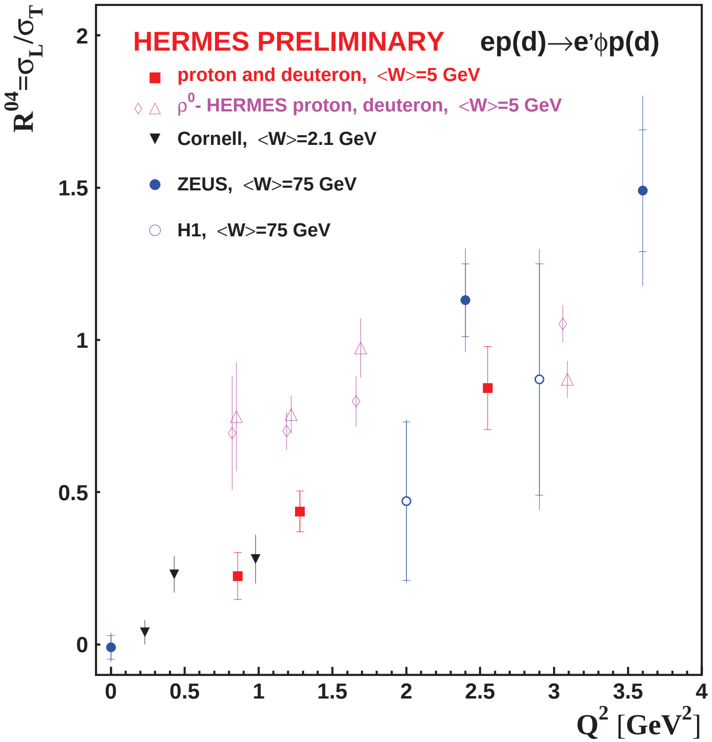
- Steep falling of the cross section observed both at high and low energy.
- No numerical comparison

Q^2 dependence

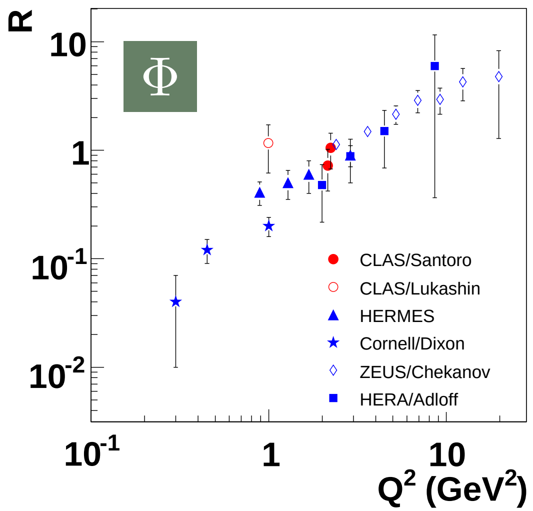
- $\sigma(Q^2)$: $\sigma_L \propto Q^{-6}$; $\sigma_T \propto Q^{-8}$ but modified by gluon pdf Q^2 depend., quark Fermi motion and virtuality, $\alpha_s(Q^2)$, higher order.







$R = \frac{\sigma_L}{\sigma_T}$

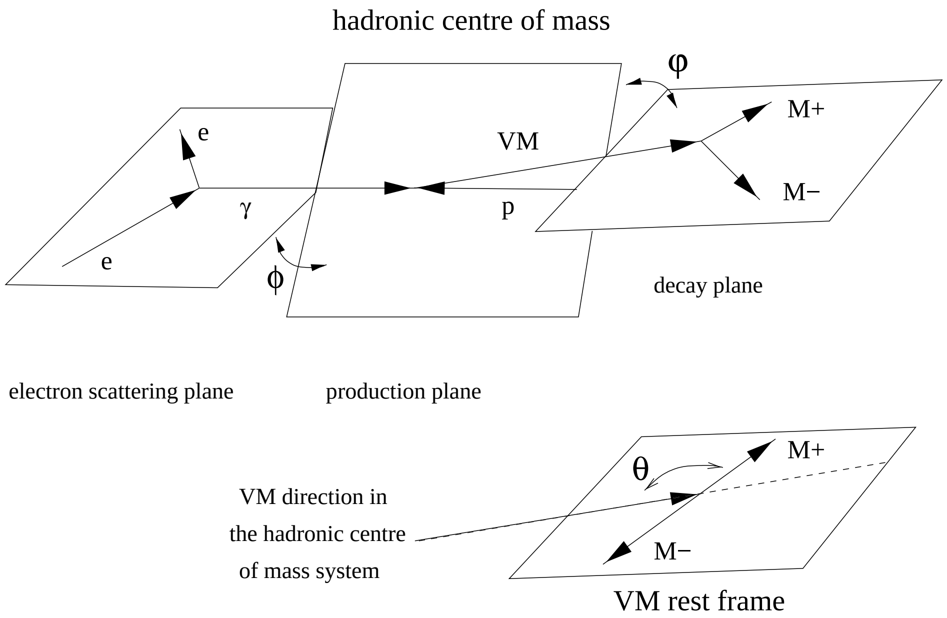


- At low energy, significant difference between ρ and ϕ.
- For ρ at low W: already significant σ_L at small Q^2

SPIN DENSITY MATRIX ELEMENTS

θ^* , Φ , $\varphi \Longleftrightarrow$ 15 SDMEs : $r^{ij}_{kl} \propto T_{\lambda'_\rho \lambda'_\gamma} T_{\lambda_\rho \lambda_\gamma}$

$T_{\lambda_\rho \lambda_\gamma}$: helicity amplitudes



No helicity flip: $T_{00} : \gamma_L \longrightarrow \rho_L$

$T_{11} : \gamma_T \longrightarrow \rho_T$

Single flip: $T_{01} : \gamma_T \longrightarrow \rho_L$

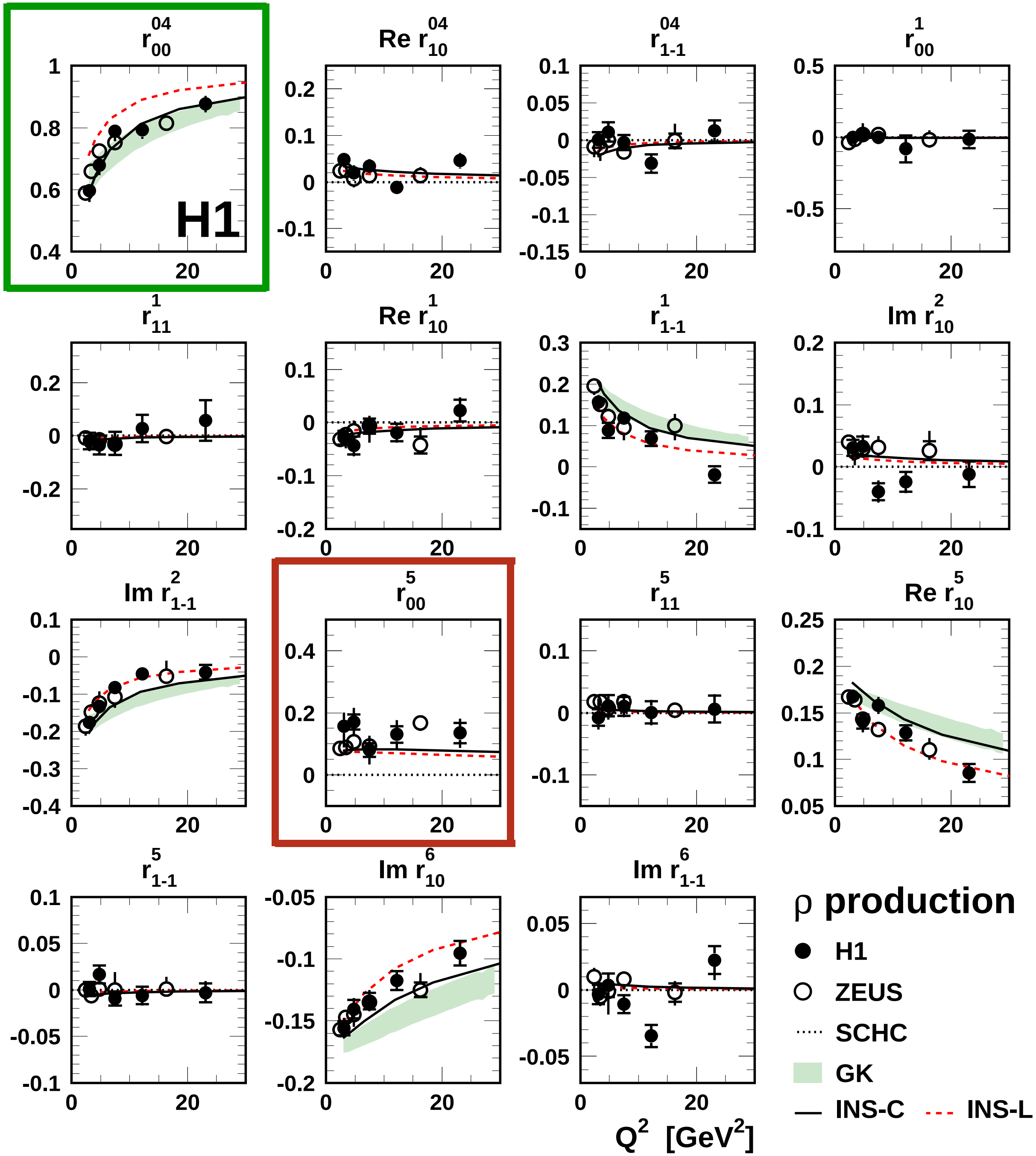
$T_{10} : \gamma_L \longrightarrow \rho_T$

Double flip: $T_{1-1} : \gamma_T \longrightarrow \rho_T$

s-Channel Helicity Conservation (SCHC): $T_{01} = T_{10} = T_{1-1} = 0$

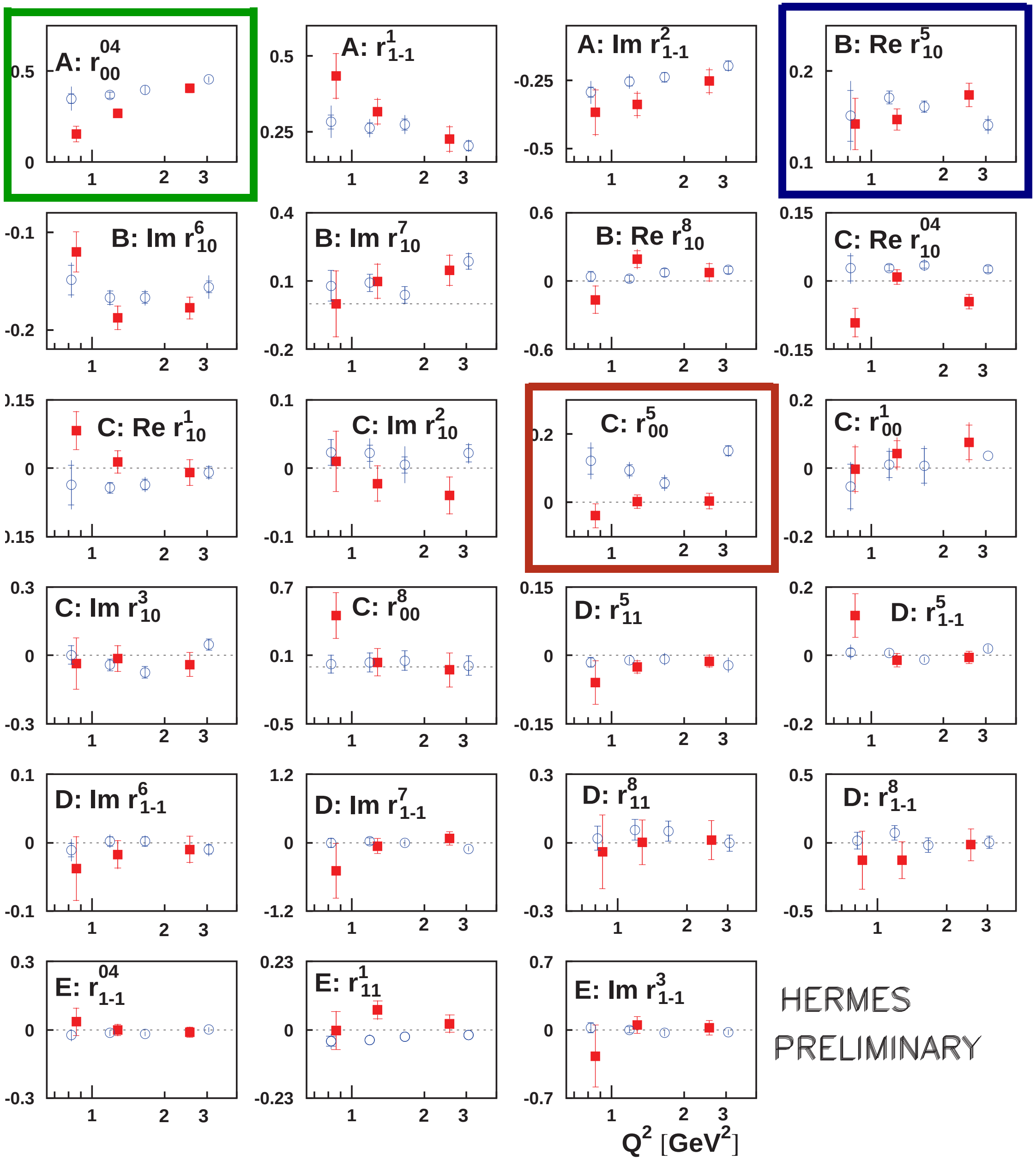
- SCHC violation (single flip $\propto \sqrt{|t|}$, double $\propto |t|$)
- pQCD Hierarchy ($|t| < Q^2$): $|T_{00}| > |T_{11}| > |T_{01}| > |T_{10}| > |T_{1-1}|$

High W: ρ Polarisation - SDMEs vs. Q^2



- r^{04}_{00} increases with Q^2
  $\leftrightarrow$ similar effects for r^1_{1-1}, Im r^2_{1-1}, Re r^5_{10} and Im r^6_{10} (in SCHC)
  $\leftrightarrow$ Fair description by Goloskokov-Kroll (GPD) model
- r^5_{00} violates SCHC (flip)
- Other SDME $\simeq 0$
- similar obs. for Φ

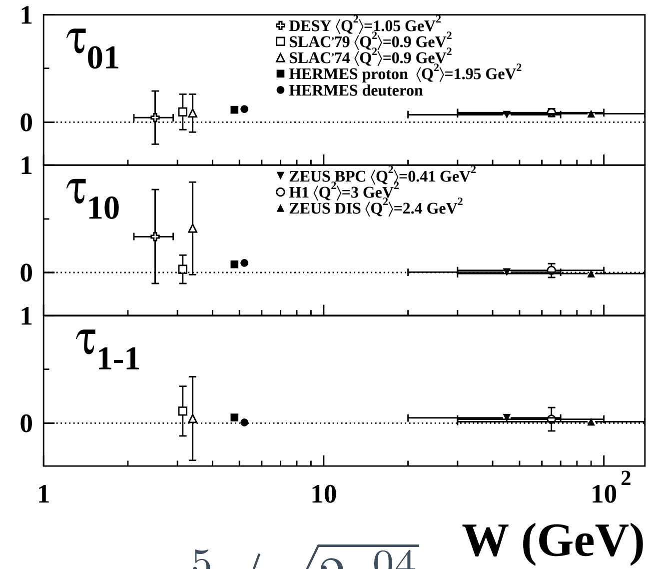
Low W: ρ and Φ Polarisation - SDMEs vs. Q^2



○ : ρ

■ : Φ

→ ρ large σ_L at low Q^2



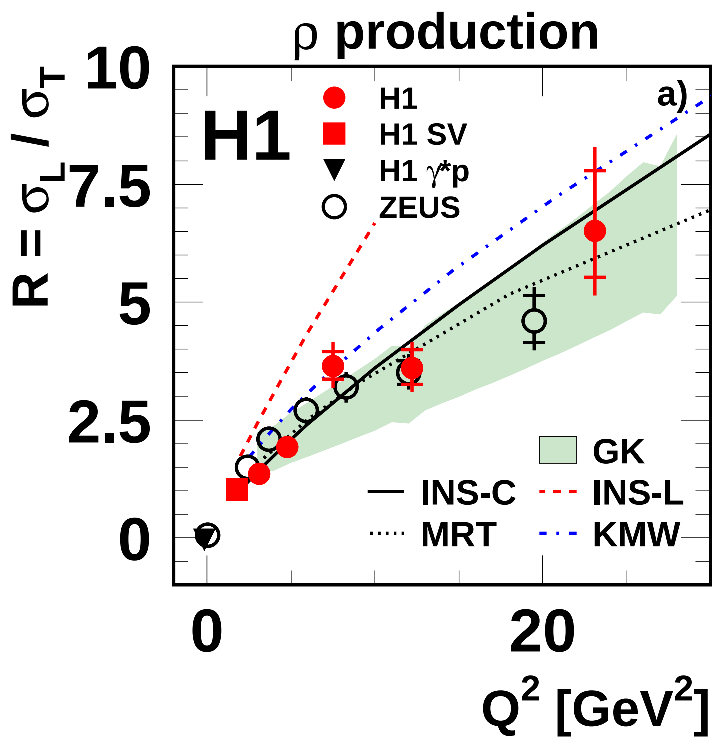
$$\tau_{01} = r^5_{00} / \sqrt{2 r^{04}_{00}}$$

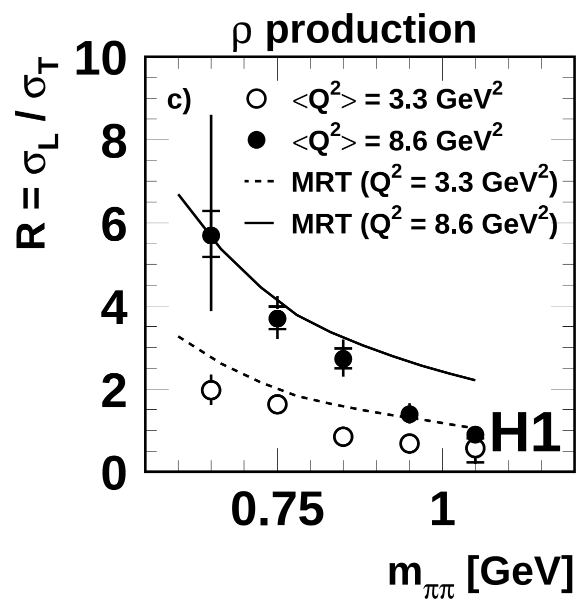
→ spin flip has no strong W dependence

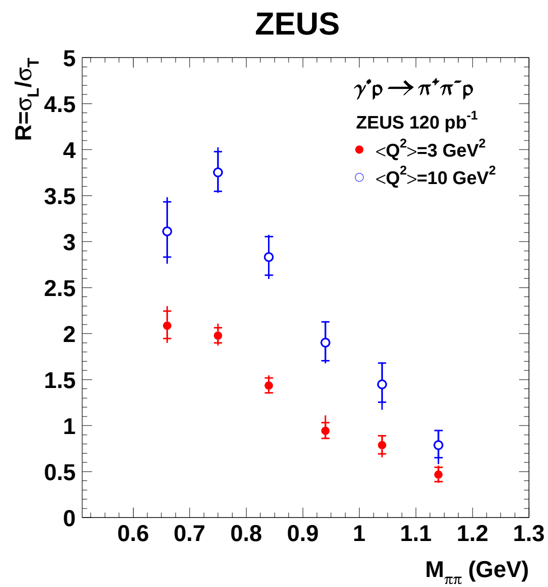
→ Re r^5_{10} : interf. $T_{00} - T_{11}$
different behaviour ρ and Φ

Polarisation - $R = \sigma_L/\sigma_T$

$$R_{SCHC} = \frac{1}{\epsilon}\frac{r^{04}_{00}}{1-\epsilon r^{04}_{00}} = \frac{|T_{00}|^2}{|T_{11}|^2}$$







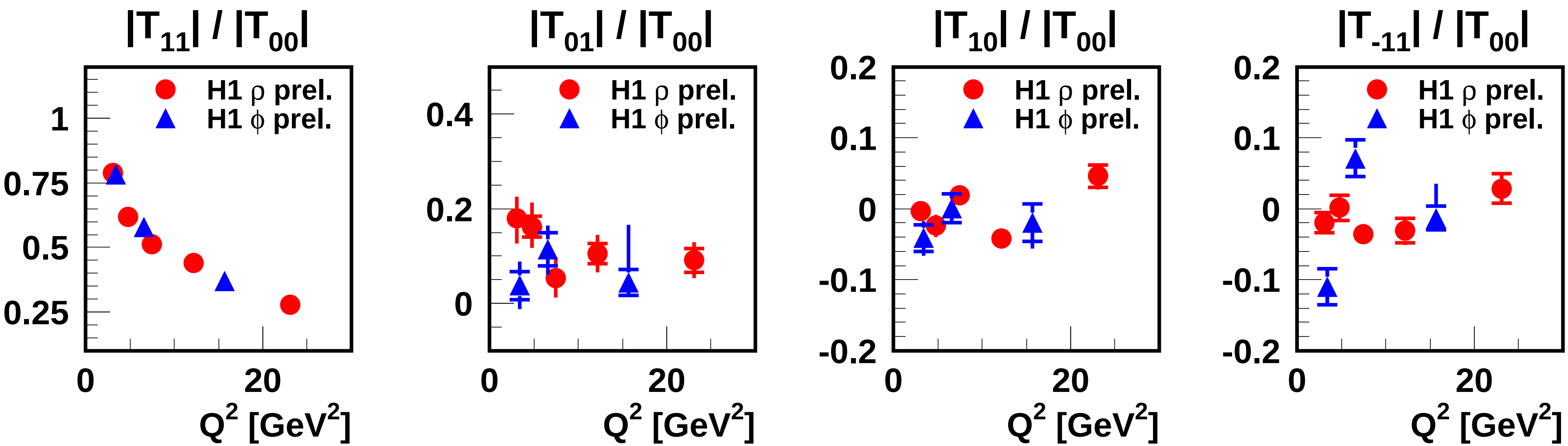
- Naive $R \propto Q^2/M^2$ - modified at high Q^2
- Similar R for ϕ and ρ
- Strong invariant mass dependence in ρ case

Polarisation - Amplitude ratios vs. Q^2

pQCD :

- $|T_{11}|/|T_{00}| \sim \frac{M}{Q} \frac{1+\gamma}{\gamma}$
- $|T_{10}|/|T_{00}| \sim -\frac{M\sqrt{|t|}}{Q^2} \frac{\sqrt{2}}{\gamma}$
- $|T_{01}|/|T_{00}| \sim \frac{\sqrt{|t|}}{Q} \frac{1}{\sqrt{2}\gamma}$

γ : gluon anomalous dim.



- $|T_{11}|/|T_{00}|$ decreases with $Q^2 \leftrightarrow \sigma_L/\sigma_T$ increases with Q^2
- $|T_{01}|/|T_{00}| > 0 \leftrightarrow$ SCHC violation
- $|T_{10}|/|T_{00}|$ and $|T_{-11}|/|T_{00}|$ are small

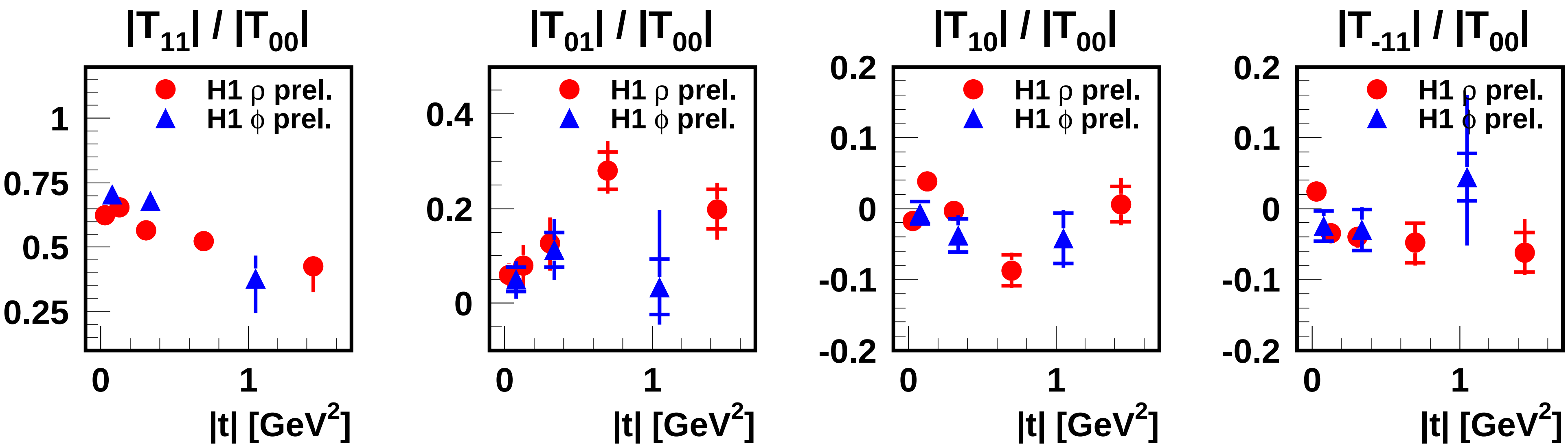
$\Rightarrow |T_{00}| > |T_{11}| > |T_{01}| > |T_{10}|, |T_{-11}| \leftrightarrow$ hierarchy observed

Polarisation - Amplitude ratios vs. $|t|$

pQCD:

- $|T_{11}|/|T_{00}| \sim \frac{M}{Q} \; \frac{1+\gamma}{\gamma}$
- $|T_{10}|/|T_{00}| \sim -\frac{M \sqrt{|t|}}{Q^2} \; \frac{\sqrt{2}}{\gamma}$
- $|T_{01}|/|T_{00}| \sim \frac{\sqrt{|t|}}{Q} \; \frac{1}{\sqrt{2}\gamma}$

γ : gluon anomalous dim.

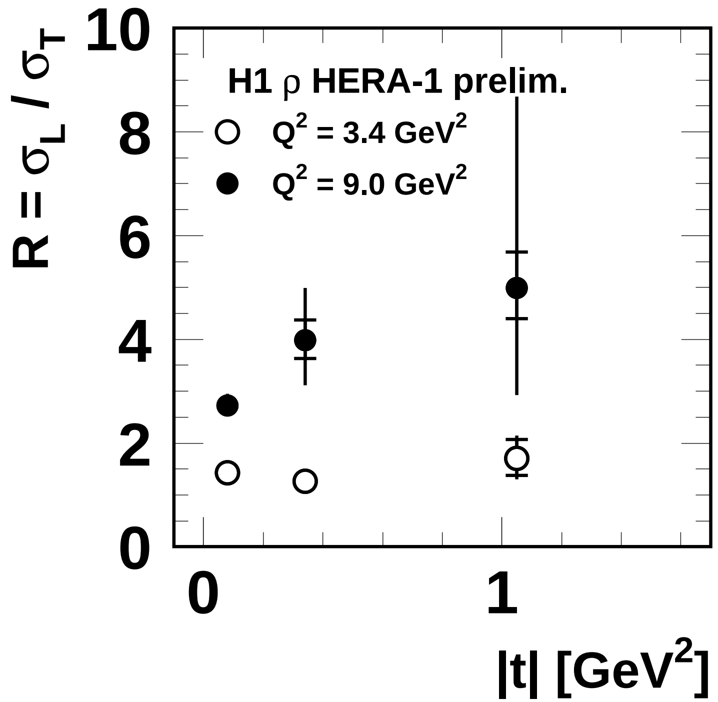


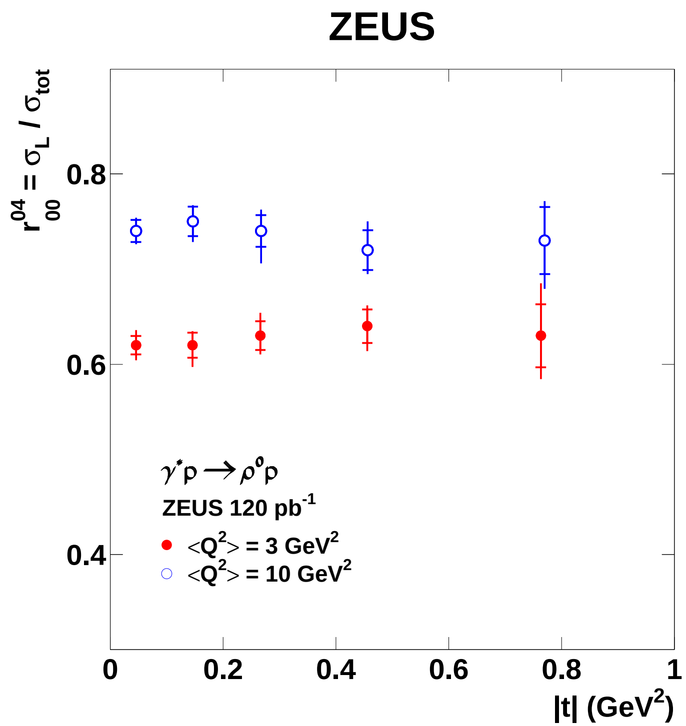
- $|T_{11}|/|T_{00}|$ decreases with $|t|$
- $|T_{01}|/|T_{00}|$ increases with $|t| \leftrightarrow$ SCHC violation increases with $|t|$
- $|T_{10}|/|T_{00}|$ and $|T_{-11}|/|T_{00}|$ are small but some $|t|$ dependence
- $|T_{11}|/|T_{00}|$ decrease partialy acompensated by $|T_{01}|/|T_{00}|$ increase

$\Rightarrow \sigma_L/\sigma_T$ is the result of partial compensations

Polarisation - $R = \sigma_L/\sigma_T$ versus t

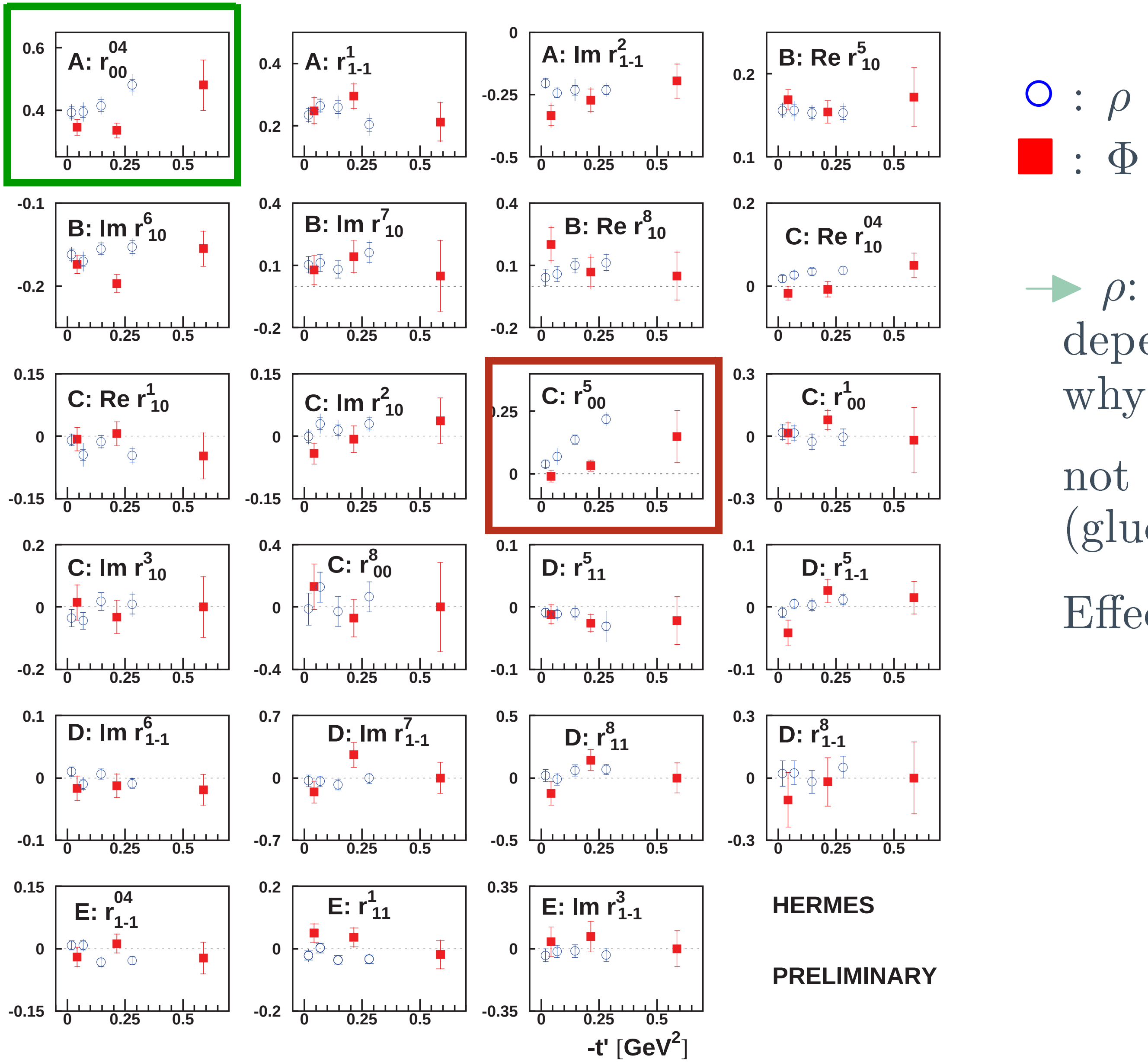
$$R_{SCHC+T_{01}} = \frac{|T_{00}|^2}{|T_{11}+T_{01}|^2}$$





- H1: R depends on t for large Q^2 $\Rightarrow b_L < b_T$!!! (σ_L more pert. than σ_T)
- Not seen by ZEUS
- due to different ρ' background treatement

Low W: ρ and Φ Polarisation - SDMEs vs. t



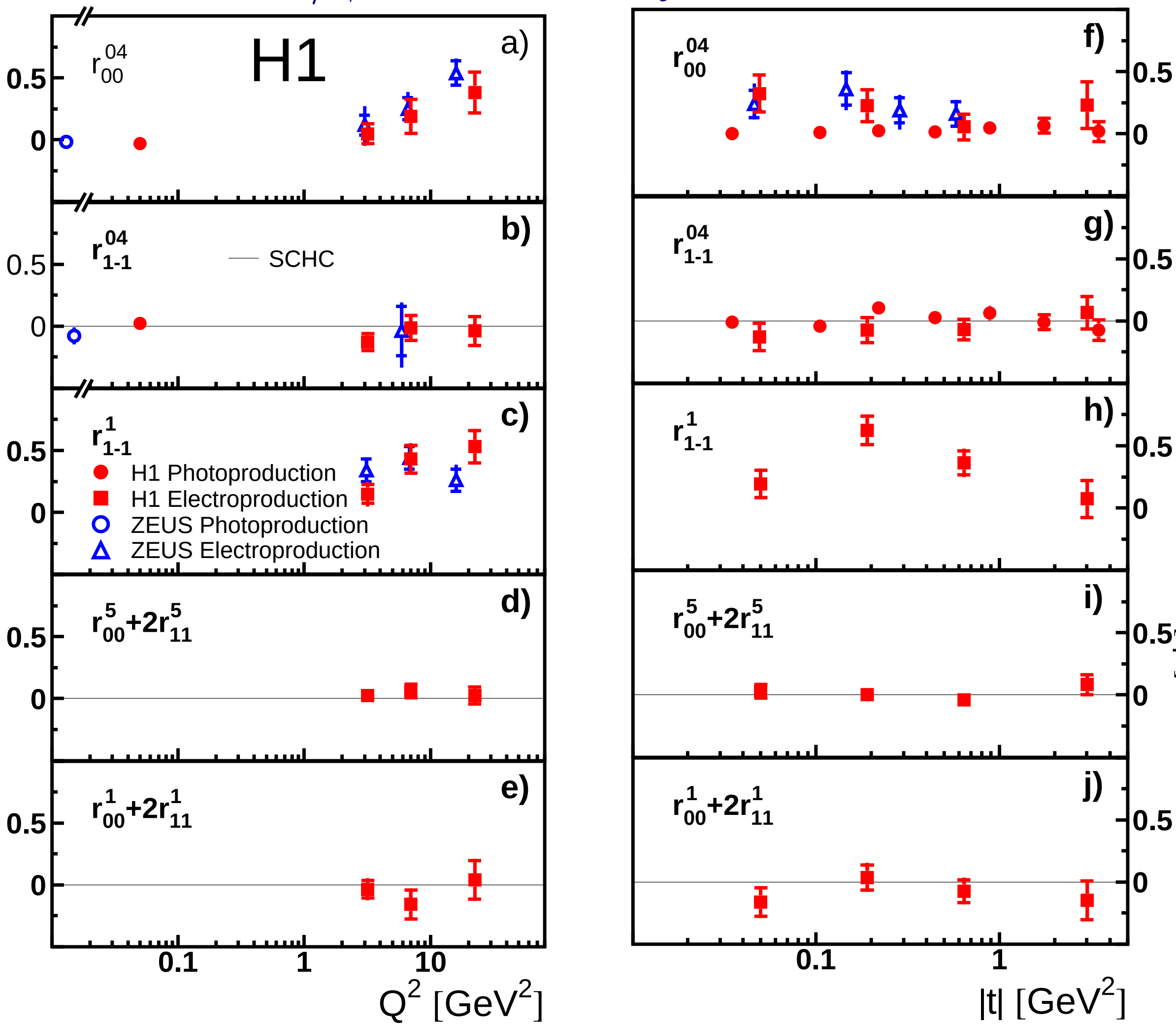
- ρ: stronger spin flip dependence with t
  why ?

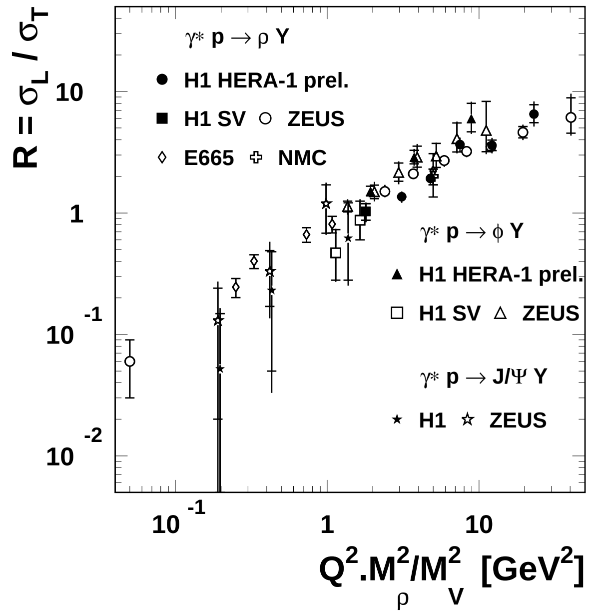
  not observed at high W (gluon dominated)

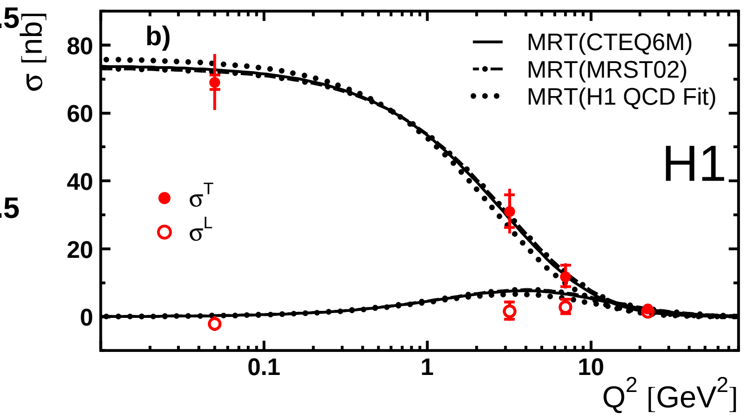
  Effect of $t_{\min}$?

J/ψ Polarisation

J/ψ SDME vs Q^2 and t:

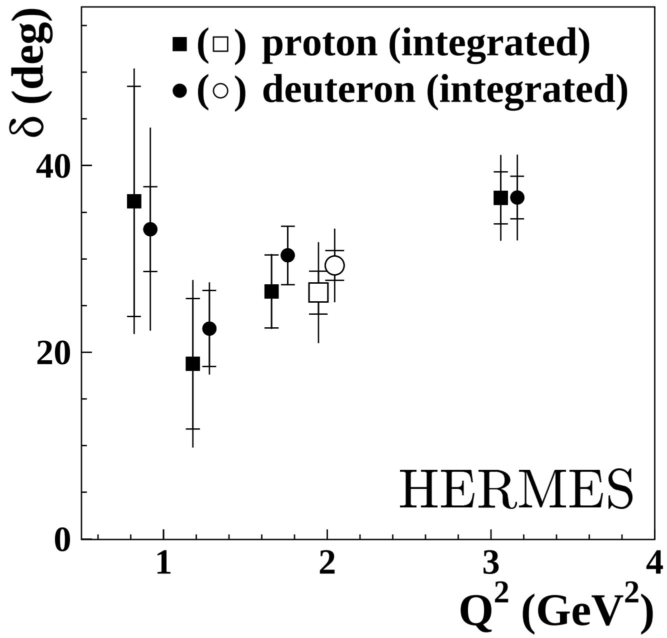


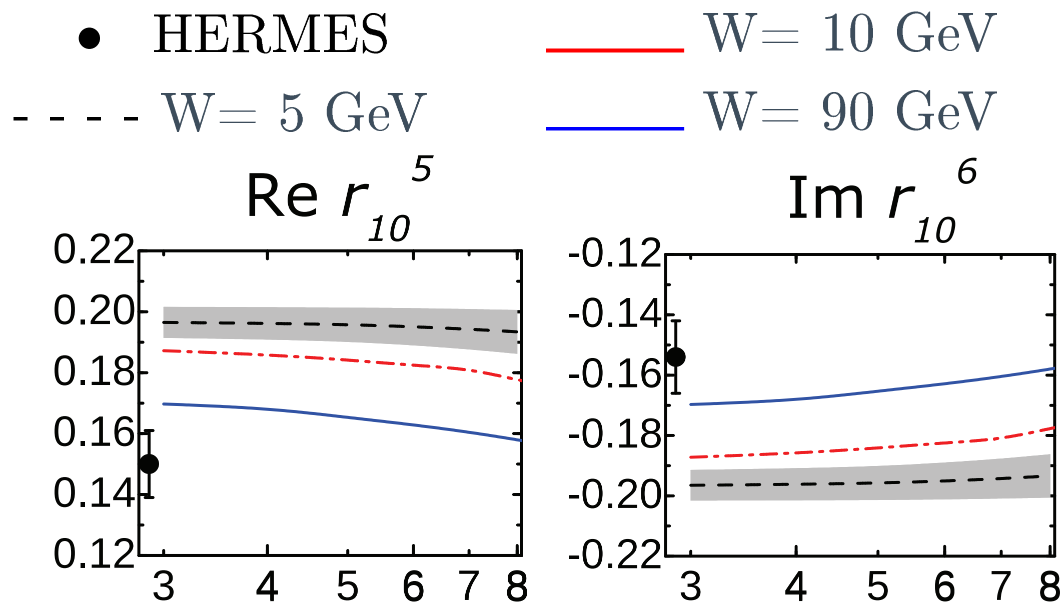




- J/ψ SDME compatible with SCHC: non-relativistic WF
- Common behaviour of R for all VM vs. $Q^2 M_\rho^2/M_{VM}^2$
- J/ψ mostly transverse

Amplitude phase



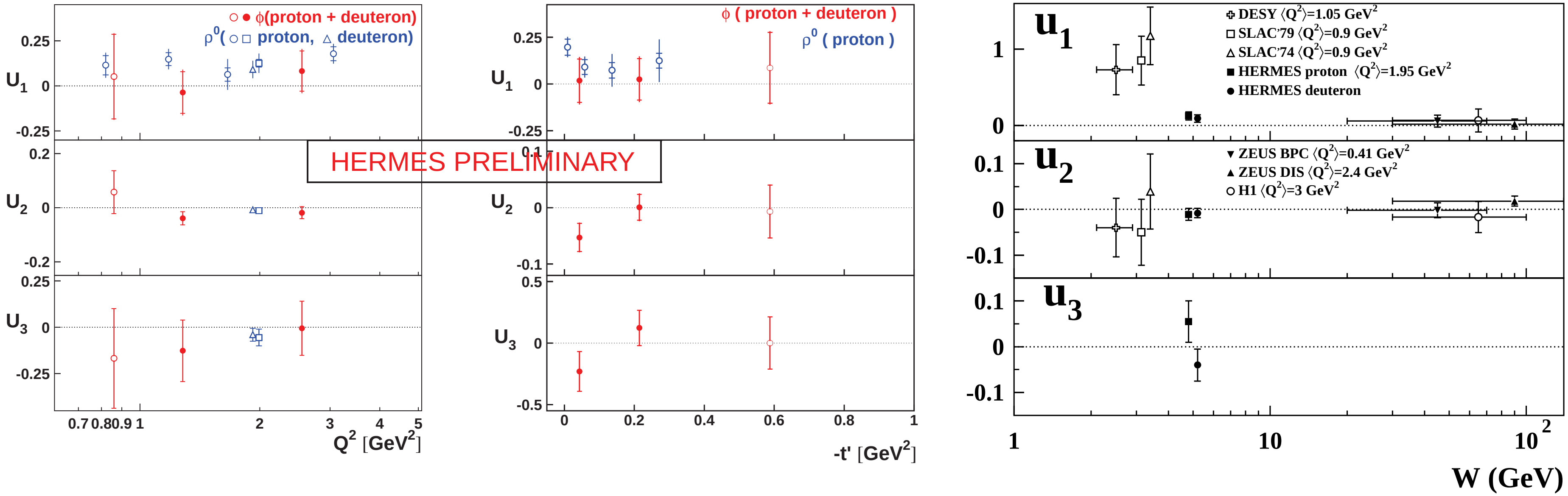


$$tan\ \delta = \frac{Im(T_{11}/T_{00})}{Re(T_{11}/T_{00})} \sim \mathrm{Re}\ r^5_{10} - \mathrm{Im}\ r^6_{10}$$

- Increase with Q^2(HERMES data)
- Expected to be fully imaginary at high energy.
- Not well described by GPD based model of GK (3.1^o at HERMES energy) .

(Un)Natural Parity Exchange

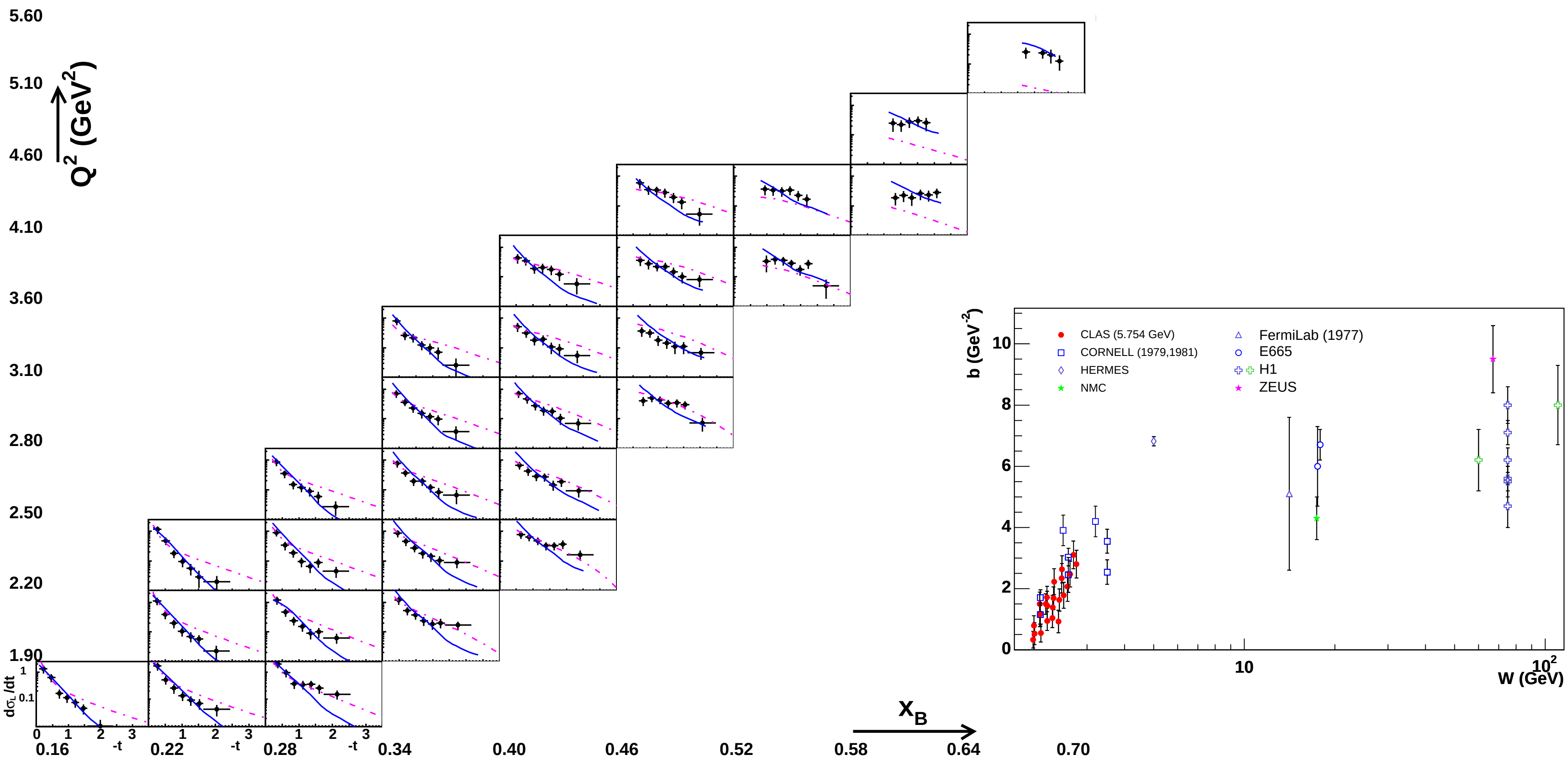
Natural-parity exchange: interaction mediated by a particle of 'natural' parity: scalar ($J^P = 0^+$ like $I\!P$) or vector (1^- like ρ, ω, a_2).
Unnatural-parity exchange: pseudoscalar (0^- like π, η) or axial meson (1^+).



$$U1 = 1 - r^{04}_{00} + 2r^{04}_{1-1} - 2r^{1}_{1-1} - 2r^{1}_{11} \quad U2 = r^{5}_{1-1} + r^{5}_{11} \quad U3 = r^{8}_{1-1} + r^{8}_{11}.$$

- Only observed for ρ (not for Φ).
- no Q^2dependence (naively $\sim 1/Q^2$).
- Important at low W (valence quark exchange).
- More pronouced at low t ? (pion pole ?).
- Possible CLAS measurement ?

GPD: Generalised D term: VGG model



• Using a "generalised" D term, the GPD based model VGG can reproduce the (t, x) correlation a priori not in the D term.

• It recover a classic D term for $t \longrightarrow 0$ and respect the Form Factors boundary conditions.

Conclusions

The vector meson exclusive production is an important tool to understand the transition between low-energy hadronic and high energy partonic domains of QCD

Large variety of measurements at low as at high energies:

- $\rho, \phi, J/\psi, \Upsilon, \gamma, ...$
- large kinematic domain in Q^2, W, t
- σ complemented by helicity ampl. give a unique insight to the dynamics.

Rich field for QCD understanding:

- global understanding of the gluon and sea contributions over more than 2 orders of magnitude in energy
- precision in the soft to hard transition: W dep., t dep.
- reasonable description of L/T separation and spin flip
- The strong rise of ρ cross sec. towards low W has still to be understood.
- Is the hand-bag model still valid or should the GPDs be adapted like e.g. in VGG model ?

Back-up Slides

VM theory: Dipole approach and k_T factorisation

Dipole approach - Saturation :

Shown here: C.Marquet, R.Peschanski, G.Soyez [hep-ph/0702171]

- $\sigma_{q\bar{q}-p}$ extracted from fits to inclusive data (F_2) with geometric scaling.
- Fits may include VM data as well (see later) and QCD evolution at high Q^2.

k_T factorisation - BFKL pomeron:

Shown here: I.Ivanov, N.Nikolaev, A.Savin [hep-ph/0501034]

- Conjugate approach to dipole one in "k_T space".
- $\sigma_{q\bar{q}-p}$ computed from k_T-unintegrated gluon pdf $\mathcal{F}(x, \vec{\kappa})$:

$$\sigma_{q\bar{q}-p} = 4\pi/3 \int d^2\vec{\kappa}/\kappa^4 \ \mathcal{F}(x, \vec{\kappa}) \ \alpha_s(\mu^2) \ [1 - \exp(i\vec{\kappa}\vec{r})]$$

N.B: for small dipole,

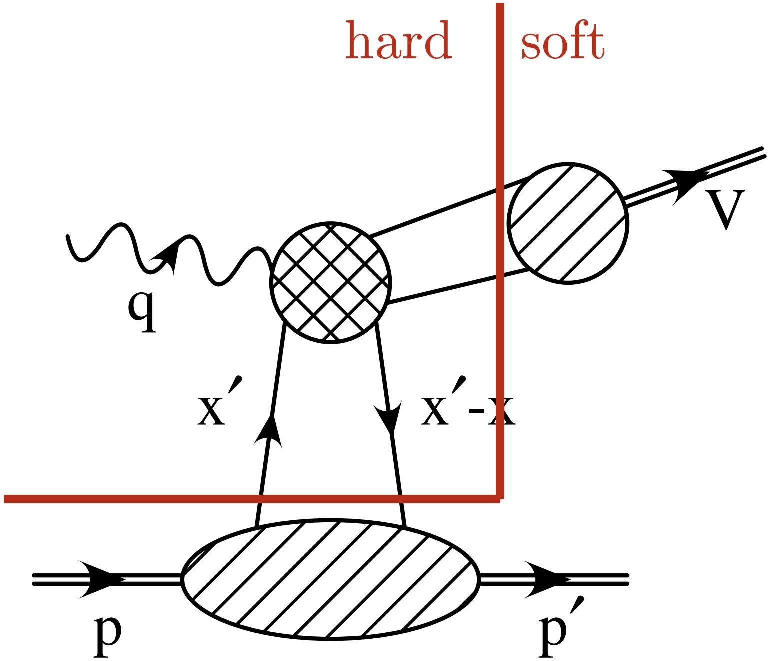
$\sigma_{q\bar{q}-p} \simeq \pi^2/3 \ r^2 \ \alpha_s(\mu^2) \ G(x, \mu^2)$ with $\mu^2 = A/(z(1-z)Q^2 + m_q^2)$; $A = 9 - 10$

$$\longrightarrow \sigma_T \propto (Q^2 + M_V^2)^{-4} \ [\alpha_s(\mu^2) \ G(x, \mu^2)]^2$$

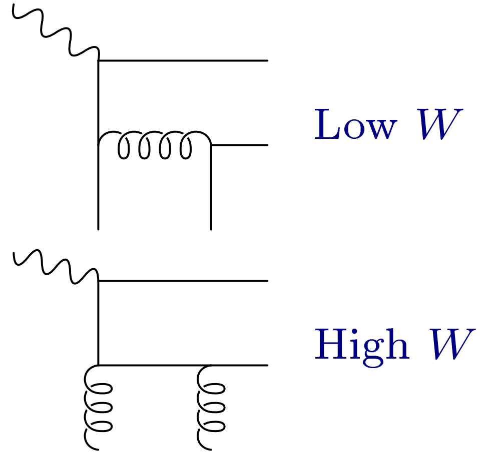
$$\longrightarrow \sigma_L \propto Q^2/M_V^2 \ (Q^2 + M_V^2)^{-4} \ [\alpha_s(\mu^2) \ G(x, \mu^2)]^2$$

VM theory: Collinear factorisation

QCD factorisation theorem valid for leading power of Q in DIS:
Collins, Frankfurt and Strikman [hep-ph/9611433]



Typical LO diagrams for H_{ij}:



$$\mathcal{A}_{\gamma^{(*)}p\to Vp} = \sum_{i,j}\int_0^1 dz \int dx' \; f_{i/p}(x', x'-x, t, \mu) \; H_{ij}(Q^2 x'/x, Q^2, z, \mu) \; \Psi_j^V(z,\mu)$$

where $f_{i/p}$: non-forward PDF ($x' \neq x' - x$, t dependant) $\rightarrow$ GPD's

H_{ij}: hard scattering m.a. ; Ψ_j^V: VM wave fct

Theorem is proven for γ_L ; extended/assumed for γ_T in many models
Shown here: S.Goloskokov and P.Kroll [hep-ph/07083569]

Polarisation - Retrieving Amplitude ratios

Assume purely imaginary amplitudes $\longrightarrow$ phase $= \pm 1$!

$\longrightarrow$ Extract $|T_{11}|/|T_{00}|$, $|T_{01}|/|T_{00}|$, $|T_{10}|/|T_{00}|$ and $|T_{-11}|/|T_{00}|$ from fit to the 15 SDMEs:

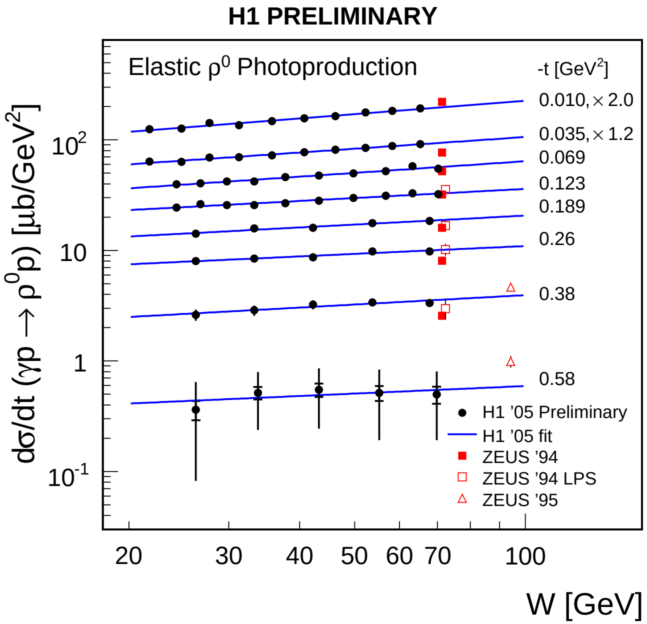
$$
\begin{aligned}
r^{04}_{00} &= B\ (\varepsilon + \beta^2) \\
\mathrm{Re}\, r^{04}_{10} &= B/2\ (2\varepsilon\delta + \beta\alpha - \beta\eta) \\
r^{04}_{1-1} &= B\ (\alpha\eta - \varepsilon\delta^2) \\
r^{1}_{00} &= -B\ \beta^2 \\
r^{1}_{11} &= B\ \alpha\eta \\
\mathrm{Re}\, r^{1}_{10} &= B/2\ \beta(\eta - \alpha) \\
r^{1}_{1-1} &= B/2\ (\alpha^2 + \eta^2) \\
\mathrm{Im}\, r^{2}_{10} &= B/2\ \beta(\alpha + \eta) \\
\mathrm{Im}\, r^{2}_{1-1} &= B/2\ (\eta^2 - \alpha^2) \\
r^{5}_{00} &= \sqrt{2} B\ \beta \\
r^{5}_{11} &= B/\sqrt{2}\ \delta(\alpha - \eta) \\
\mathrm{Re}\, r^{5}_{10} &= B/(2\sqrt{2})\ (2\beta\delta + \alpha - \eta) \\
r^{5}_{1-1} &= B/\sqrt{2}\ \delta(\eta - \alpha) \\
\mathrm{Im}\, r^{6}_{10} &= -B/(2\sqrt{2})\ (\alpha + \eta) \\
\mathrm{Im}\, r^{6}_{1-1} &= B/\sqrt{2}\ \delta(\alpha + \eta)
\end{aligned}
$$

$$
\begin{aligned}
\alpha &= |T_{11}|/|T_{00}| \\
\beta &= |T_{01}|/|T_{00}| \\
\delta &= |T_{10}|/|T_{00}| \\
\eta &= |T_{-11}|/|T_{00}|
\end{aligned}
$$

$$
\begin{aligned}
B &= \frac{1}{N_T + \varepsilon N_L} = \frac{R}{1 + \varepsilon R} \\
N_T &= \alpha^2 + \beta^2 + \eta^2 \\
N_L &= 1 + 2\delta^2
\end{aligned}
$$

Shrinkage : $\alpha'_{I\!P}$ measurements

H1 ρ photoproduction measurements: $\frac{d\sigma}{dt}(W) \propto e^{b_0 t}\, W^{4(\alpha_{I\!P}(t)-1)}$

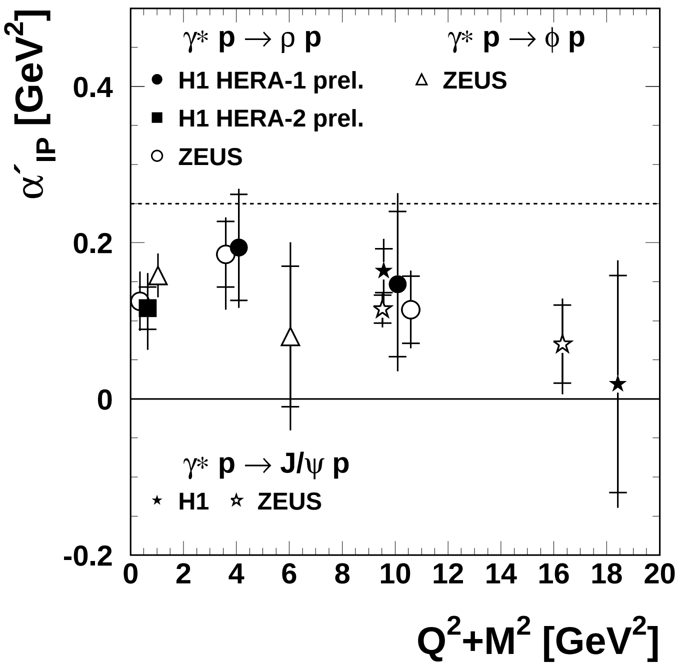


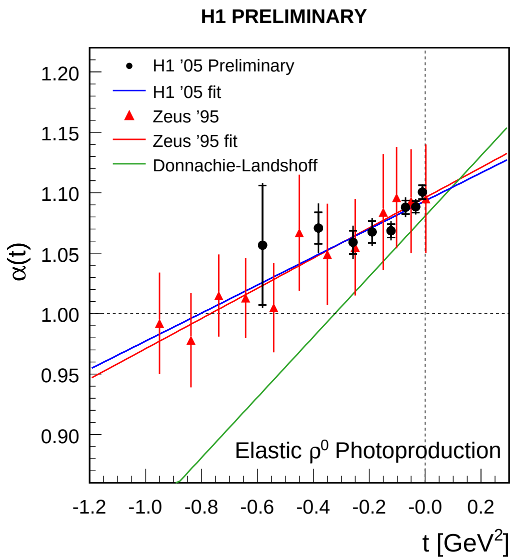
1. Study W depend. in bins of t:

   $\rightarrow$ Fit: $W^{\delta} \rightarrow \alpha_{I\!P}(t) = 1 + \delta/4$

2. Study $\alpha_{I\!P}(t)$ trajectories:

   $\rightarrow$ Fit: $\alpha_{I\!P}(t) = \alpha_{I\!P}(0) + \alpha'_{I\!P}\, t$

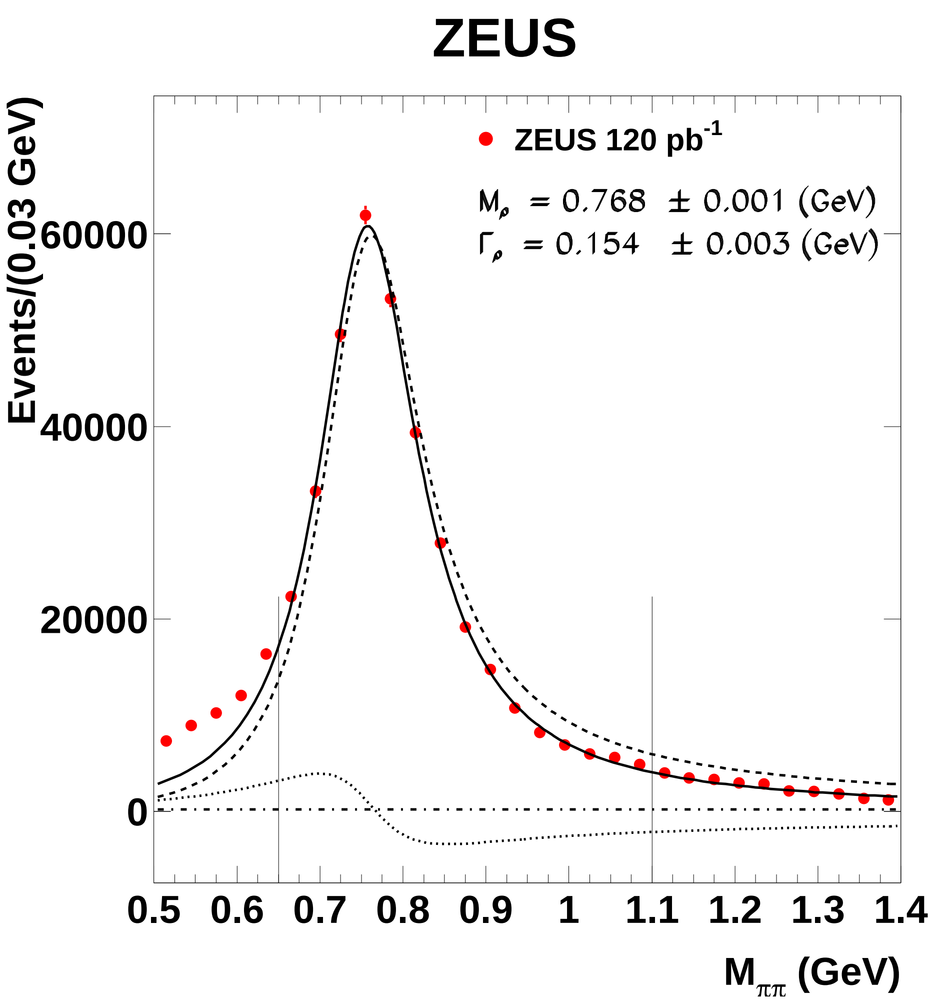




$\Rightarrow$ For all VM, $\alpha'_{I\!P}$ smaller than 0.25 (DL, $p\bar{p}$)

(cf BFKL, multiple $I\!P$ exchange)

Rho mass


ZEUS
ZEUS 120 pb^{-1}
M_ρ = 0.768 ± 0.001 (GeV)
Γ_ρ = 0.154 ± 0.003 (GeV)
Events/(0.03 GeV)
60000
40000
20000
0
0.5 0.6 0.7 0.8 0.9 1 1.1 1.2 1.3 1.4
$M_{\pi\pi}$ (GeV)